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A SURVEY OF $\nu_\mu e$ PHYSICS WITH EMPHASIS ON RECENT FERMILAB RESULTS*

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From both an experimental and an historical point of view it is particularly appropriate to summarize the development of $\nu_\mu e^-$ physics at this time. Historically, it was ten years ago last week that the announcement (see Figure 1) of the first $\nu_\mu e^-$ event was sent from Aachen to the other members of the Gargamelle Collaboration. The event, shown in Figure 2, is of a single electron identified via its characteristic bremsstrahlung and curvature. The significance of this event far exceeds its visual impact. With a background[1] of less than .03 events, it became the first solid indication for the existence of the weak neutral current. On the experimental front, the investigation of the $\nu_\mu e$ interaction is about to enter a new phase, having graduated from experiments yielding 2-3 events to those which will be analyzing hundreds of events. With these high statistics experiments it should be possible to study the differential as well as the total crosssections of $\nu_\mu e$ and $\bar{\nu}_\mu e$ scattering. Before reviewing the increasingly sophisticated methods with which the experimentalists have studied $\nu_\mu e$ scattering, let's briefly recall how the theoretical interpretation has evolved.

PHENOMENOLOGY OF $\nu_\mu e$ SCATTERING

The theory of $\nu_\mu e$ scattering has been covered[2] many times. It is a purely leptonic neutral current interaction not complicated by a (relatively) poorly known hadronic component. Let me here directly introduce the vector and axial vector coupling constants g_V and g_A in the effective Lagrangian.

$$L_{eff} = \frac{G}{\sqrt{2}} (\bar{\nu}_\mu \gamma_\alpha (1+\gamma_5)\nu_\mu)(\bar{e}\gamma_\alpha(g_V+g_A\gamma_5)e) \qquad 1)$$

It is the accurate determination of these two quantities- g_V and g_A - which has been the goal of the last decade of experiments. These constants appear as measurable quantities in the cross sections

$$\frac{d\sigma}{dy} = \frac{G^2 m_e}{2\pi} E_\nu \left[(g_V + g_A)^2 + (g_V - g_A)^2 \ (1-y)^2 \right] \qquad 2)$$

with $y = E_e/E_\nu$. The $\bar{\nu}$ cross section is obtained by changing the sign of g_A $(+ \rightarrow -)$ in the above formula.

III. PHYSIKALISCHES INSTITUT
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Dear Colleagues,

Enclosed you will find photographs of a single electron event found here at Aachen. The main vertex is at x = -163.7, y = 6.9, z = 13.9. The measured momentum (by curvature) is P = ·359 ± ·035 and the angle θ = ·025 radians. This event thus qualifies as a leptonic neutral current candidate according to our previously defined constraints.

We have found the use of photographs to be extremely helpful in the analysis of the leptonic neutral current question. We would propose then that photographs of all events having a single electron from the main vertex be collected at the next collaboration meeting. These would include:

1) Any other leptonic neutral current candidates
2) All ν_e and $\bar{\nu}_e$ events
3) Any event classified as having a $\mu^\pm$ candidate and an $e^\pm$ candidate.

Sincerely,

(For the Aachen Group)

Jorge G. Morfín

Figure 1. Letter sent to the Gargamelle Collaboration announcing the discovery of the first $\bar{\nu}_\mu e$ event.

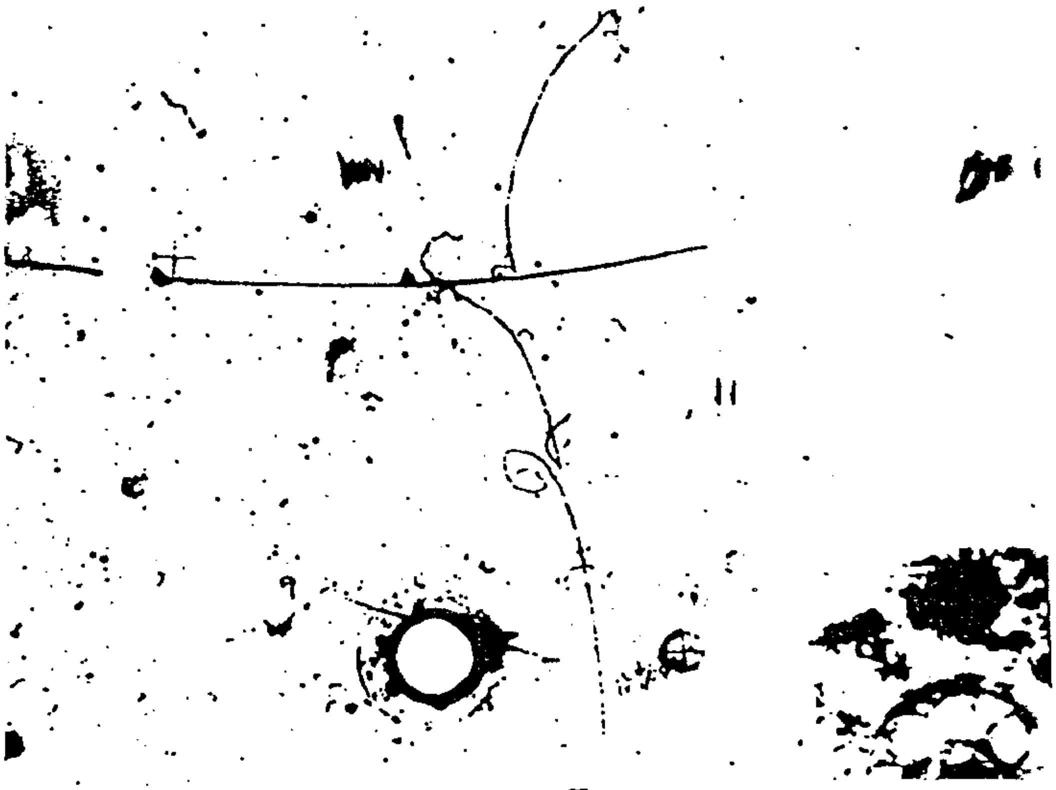

Figure 2. One view of the first $\bar{\nu}_\mu e$ event found by the Gargamelle Collaboration.

Most experimental results of $\nu_\mu e$ scattering are presented as contours in the g_V - g_A plane. Note that if equation 2 is integrated over y to give the total cross sections σ and $\bar{\sigma}$, they each describe an ellipse in the g_V - g_A plane. Because of this quadratic dependence of $\sigma(\bar{\sigma})$ on the coupling constants, there is a four-fold ambiguity in the values of g_V and g_A no matter how accurately the total cross sections are measured. Even with measurements of $d\sigma(\bar{\sigma})/dy$, which the new high statistics experiments can (in principle) provide, the ambiguity still remains twofold.

We need not wait for these measurements of the y distribution to reduce the number of possible solutions. The interaction of ν_e and $\bar{\nu}_e$ with electrons is also described with g_V and g_A. However, since $\bar{\nu}_e e$ scattering also has a charged current contribution, the differential cross section becomes

$$\frac{d\bar{\sigma}(\bar{\nu}_e e)}{dy} = \frac{G^2 m_e}{2\pi} E_\nu \left[(g_V - g_A)^2 + (g_V + g_A + 1)^2 \ (1-y)^2 \right] \qquad 3)$$

This introduces an ellipse in the g_V - g_A plane oriented like the $\bar{\nu}_\mu e$ ellipse, but with an offset toward the $-g_V$, $-g_A$ quadrant.

To further limit the possible number of solutions we must leave the realm of purely leptonic scattering and utilize one of the many elegent legacies left to us by the late J.J. Sakurai, the "factorization" hypothesis of Hung and Sakurai.[3] They noted that the most general neutral current formulation involves ten coupling constants:

g_V and g_A: ν-e scattering

α, β, γ and δ: ν-quark scattering (I=0,1;V and A)

$\tilde{\alpha}$, $\tilde{\beta}$, $\tilde{\gamma}$ and $\tilde{\delta}$: e-quark parity violating scattering

They derived an equality, in terms of the above coupling constants to be;

$$C_\nu^2 = 2g_A \frac{\alpha}{\tilde{\alpha}} = 2g_A \frac{\gamma}{\tilde{\gamma}} = 2g_V \frac{\beta}{\tilde{\beta}} = 2g_V \frac{\delta}{\tilde{\delta}} \qquad 4)$$

This established a relationship between the three types of neutral current interactions νe, νq, and eq, and provides a further constraint on g_V and g_A

$$\frac{g_V}{g_A} = \frac{(\alpha + \gamma/3)}{(\tilde{\alpha} + \tilde{\gamma}/3)} \frac{(\tilde{\beta} + \tilde{\delta}/3)}{(\beta + \delta/3)} \qquad 5)$$

With the introduction of factorization, the allowed values of g_V and g_A become limited as in Figure 3.

This then is the most general model-independent way of fixing values of the initial coupling constants g_V and g_A. By introducing factorization we increased the number of coupling constants involved in the interpretation to ten which we quickly reduced-by expression 5) (and the assumption that $C_\nu^2 = 1$) -to seven. Further reductions in the number of constants is possible but only at the cost of model independence. Assuming general SU(2) $\otimes$ U(1) introduces two further constraints[4] which reduces the overall number of constants to five: ρ, the ratio of charged current(CC) to neutral current(NC) coupling "strengths"; T_{3R}^u, T_{3R}^d, T_{3R}^e, the right handed isospin assignments of the u-quark, d-quark and electron; and Θ, the electro-weak mixing angle. In terms of this new set of coupling constants our initial pair of constants can be expressed as

$$g_V = \frac{1}{2} \left(-1 + 2T_{3R}^e + 4 \sin^2\Theta\right) \qquad 6)$$

$$g_A = \frac{1}{2} \left(-1-2\, T_{3R}^e\right)$$

A further and final reduction in the number of involved constants brings us to the minimal SU(2) X U(1) model otherwise known as the "standard" or Weinberg-Salam model [5]. In this model, the strengths of NC and CC interactions are equal ($\rho=1$) and all right handed components are iso-singlets ($T^{u,d,e,}_{3R} = 0$). Thus we have just one remaining constant, the electro-weak mixing angle commonly referred to as the Weinberg angle, Θ_w. Expression 6) reduces to the "standard" representation

$$
\begin{aligned}
g_V &= -\tfrac{1}{2} + 2\sin^2\Theta_w \\
g_A &= -\tfrac{1}{2}
\end{aligned}
\qquad 7)
$$

DEVELOPMENT OF EXPERIMENTAL TECHNIQUES

Turning now to the experimental study of $\nu_\mu e$ scattering, we will see that the sophistication of the experimentalist's interpretation of their results followed, naturally, the increasing statistical power of the experiments.

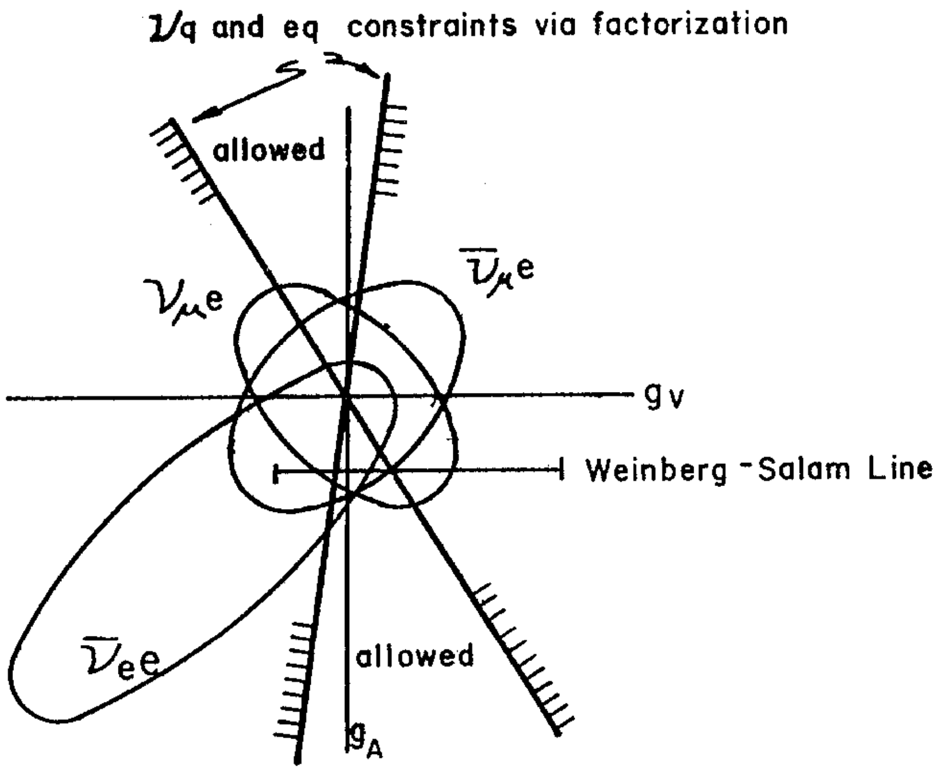

Figure 3. How the allowed region of the $g_V - g_A$ plane is reduced by the various experimental inputs.

Referring back to expression 2) it quickly becomes apparent why $\nu_\mu e$ experiments are so difficult. The quantity $G^2 m_e/2\pi$ corresponds to a cross section of $\sim 4.3 \times 10^{-42}$ cm^2 so that the rate of these purely leptonic events is down by three orders of magnitude compared to the semileptonic NC and CC interactions. This implies that not only is it difficult to acquire substantial statistics but that backgrounds, coming from NC or CC interactions, have much higher cross sections than the signal interaction. Fortunately, kinematics proves to be an indispensible aid in reducing the background to managable size. In particular an electron resulting from $\nu_\mu e$ scattering will subtend a <u>very</u> small angle with respect to the ν direction. All experiments have made use of this fact in various forms.

At the presentation of the first results[6)] and interpretation, based on $\sim$ 1 (after subtraction) $\bar{\nu}_\mu e$ event and zero $\nu_\mu e$ events found by February 1973, direct comparison was made with the minimal SU(2) X U(1) model of Weinberg and Salam. The resulting limit of $\sin^2\theta_W < 0.9$ was not a particularly bold statement - it was, however, a beginning! At the completion of the Gargamelle PS Freon experiment, with 2.6 $\bar{\nu}_\mu e$ and $\sim$ 0.7 $\nu_\mu e$ events, the limits[7)] on the mixing angle were $0.1 < \sin^2\theta_W < 0.4$.

The next experiment to study $\nu_\mu e$ scattering was the Aachen-Padova spark chamber. In general, electronic detectors will yield higher statistics but have a more difficult time separating signal from background whereas bubble chambers have limited statistics but good signal/background separation. The results of $\bar{\nu}_e e$ scattering were combined with the Aachen-Padova results (based on 9.6 $\bar{\nu}_\mu e$ events and 11.5 $\nu_\mu e$ events) by Sehgal[8)] reducing the allowed regions to two areas referred to as the g_V dominant and g_A dominant solutions as shown in Figure 4.

It was at this point in time that Fermilab experiments began contributing to the world sample of $\nu_\mu e$ events with the 15' Bubble Chamber results of a Brookhaven-Colombia collaboration. In an exposure using a heavy (64%) Ne/H mixture they determined their angular resolution to be $\sim$ 4mr and $\Delta E/E$ to vary from 10% at 2 GeV to $\sim$ 15% at 20 GeV. Results presented by N. Baker[9)] gave limits of $\sin^2\theta_W = 0.20^{+0.16}_{-0.08}$. Factorization is now used to combine: 1) the SLAC e-D results; 2) ν semileptonic NC results: 3) Gargamelle and Aachen-Padova $\bar{\nu}_\mu e$ results; 4) $\bar{\nu}_e e$ results and 5) the Colombia-BNL results to yield Figure 5. The allowed region has been reduced to the g_A dominant solution and is completely consistent with the minimal Weinberg-Salam model.

With this Fermilab 15' experiment, the era of significant contributions from Bubble Chambers to the study of $\nu_\mu e$ physics came to an end, and electronic detectors, with improved

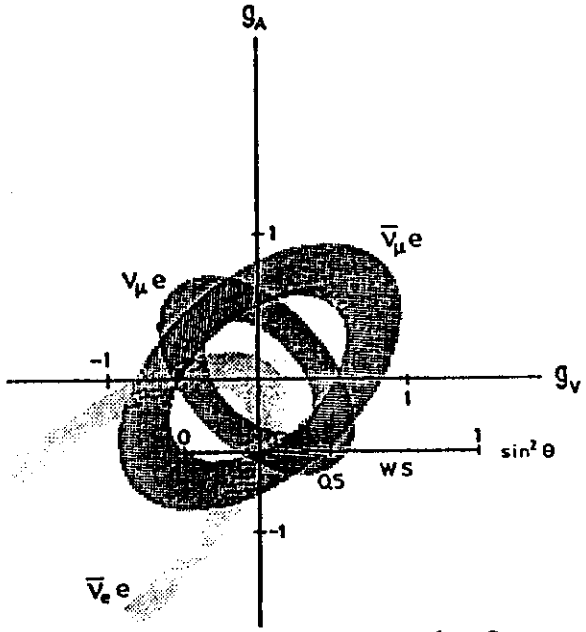

Figure 4. Allowed region of $g_V - g_A$ using the Gargamelle, Aachen Padova $\bar{\nu}_\mu e$ and the Reines $\bar{\nu}_e e$ results.

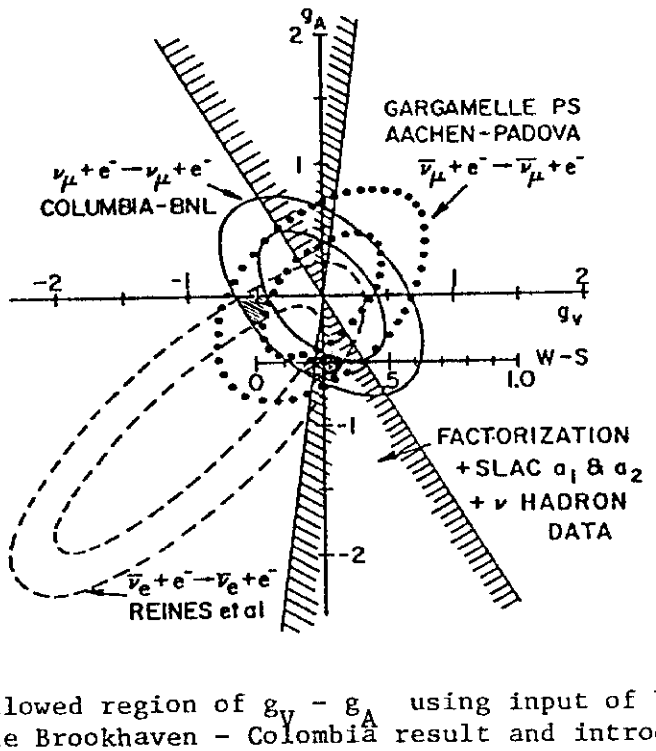

Figure 5. Allowed region of $g_V - g_A$ using input of Figure 4($\bar{\nu}$) and the Brookhaven - Colombia result and introducing the constraints from factorization.

resolutions and higher statistics, took over the lead. The results from the CHARM collaboration's experiment at CERN and the new dedicated experiment at Brookhaven will be described by others[10,11] at this conference. I will concentrate on the two Fermilab experiments beginning with the high resolution detector of the VPI-Maryland-NSF-Oxford-Peking collaboration. The apparatus consisted of 49 modules each consisting of $\sim$ 1 radiation thick Al plate, 1 MWPC and 1 layer of plastic scintillation counter. The resolution in energy was determined to be < 8%. The angular resolution is illustrated in Figure 6, taken from Reference 12., which can be assumed to be a distribution of $\Delta\Theta = \Theta$ (measured) - Θ(real). The authors quote the angular resolution as $\pm$ 5 mr (FWHM), which is an overestimate, and <u>independent of energy.</u> In fact the distribution of Figure 6 demonstrates $\langle\Delta\Theta\rangle$ = 0.36 mr with a σ of 2.65 mr. This is far better angular resolution than any other detector except, perhaps, the new Brookhaven detector and allows this collaboration to make excellent use of kinematics to separate signal from background. The final sample of 40 $\nu_\mu e^-$ events, when interpreted in the minimal model, corresponded to $\sin^2\Theta_W = 0.25^{+0.05}_{-0.03}$. Incorporating these results in the full g_V - g_A plane analysis yields Figure 7.

The second major Fermilab electronic detector experiment initially dedicated to the study of $\nu_\mu e$ scattering is experiment E-594 a Fermilab, MIT, Michigan State and Northern Illinois collaboration with participants as shown in Figure 8a. The detector, shown in Figure 8b, is a fine-grain calorimeter consisting of 608 flash tube planes (4×10^5 cells) interspersed amongst planes of iron shot and sand to give interaction mass. After every 16 flash tube planes there is a proportional tube plane used

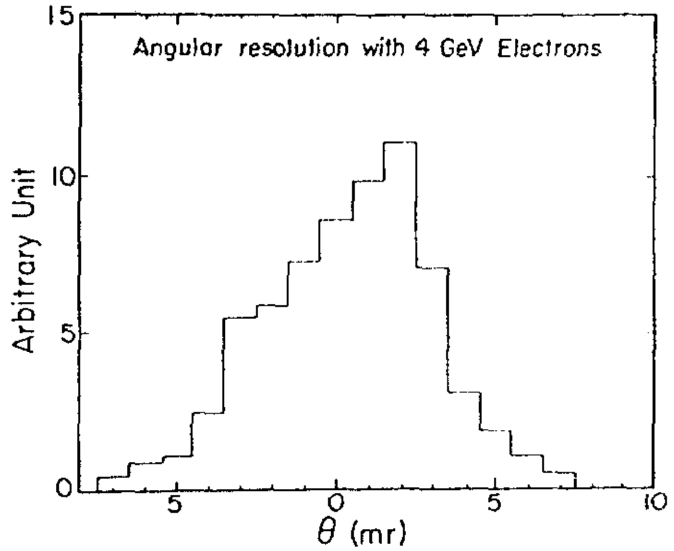

Figure 6. Measured angular resolution of UPI-Maryland - NSF-Oxford Peking detector at Fermilab.

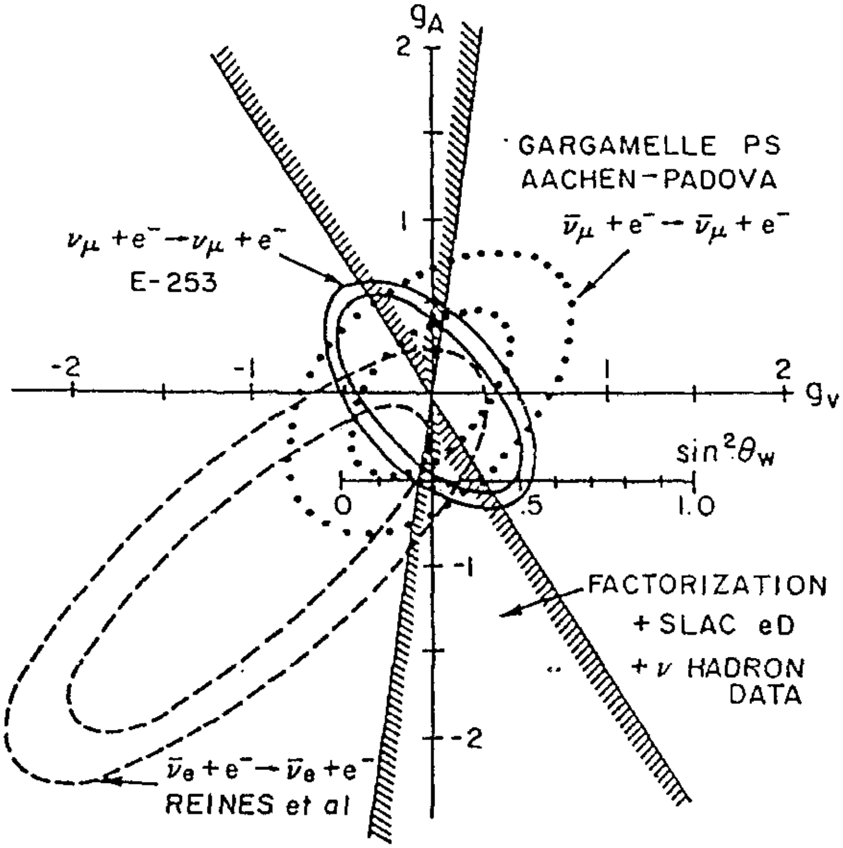

Figure 7. As in Figure 5 with the VPI -- Collaboration results replacing the BNL - Colombia results.

in triggering and energy determination of very high energy (> 75 GeV) electrons. The calorimeter was followed by a muon spectrometer consisting of three 24' and two 12' magnetized toroids with four double planes of proportional tubes to trace the muon trajectory through the toroids. In a calibration run employing electrons between 5 and 75 GeV and hadrons with 10 to 125 GeV energy, the resolution of the detector was determined to be as shown in Figure 9.

In a 1981 engineering run,[F1)] dedicated to bringing the detector up and developing triggers, $\sim 3 \times 10^{18}$ protons were directed to the Fermilab wideband neutrino beam. The resultant neutrino flux yielded 58.3K electron triggers defined as a shower with length less than 21 radiation lengths, no muon and a minimum deposited energy of $\sim$5 GeV. It was determined that this trigger was 90% efficient in detecting electrons. There were also triggers to record conventional neutral and charged current neutrino events for normalization purposes. Direct use of the fine grained nature of the calorimeter was made by examining the density of showers. Defining the density (ρ) as the number of hit

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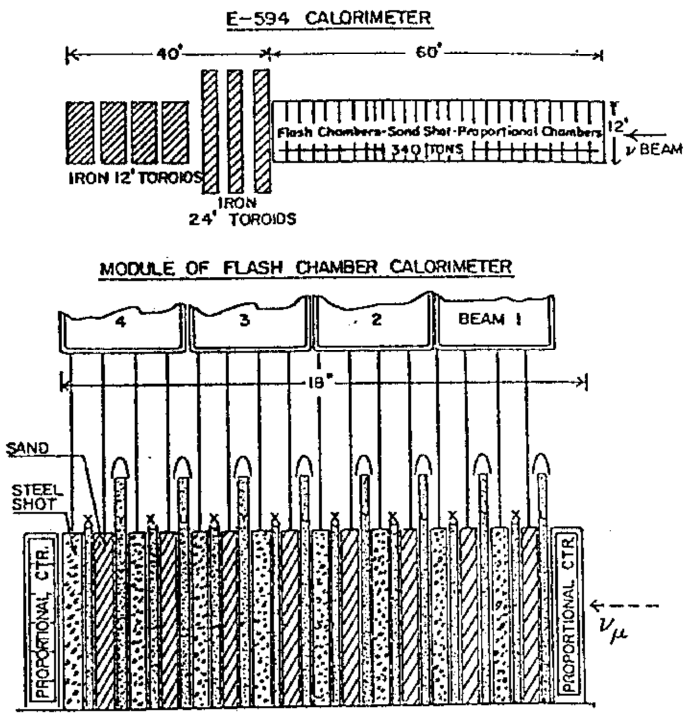

Figure 8. a) Participants of Experiment 594

b) The E-594 fine-grained Flash Tube Detector

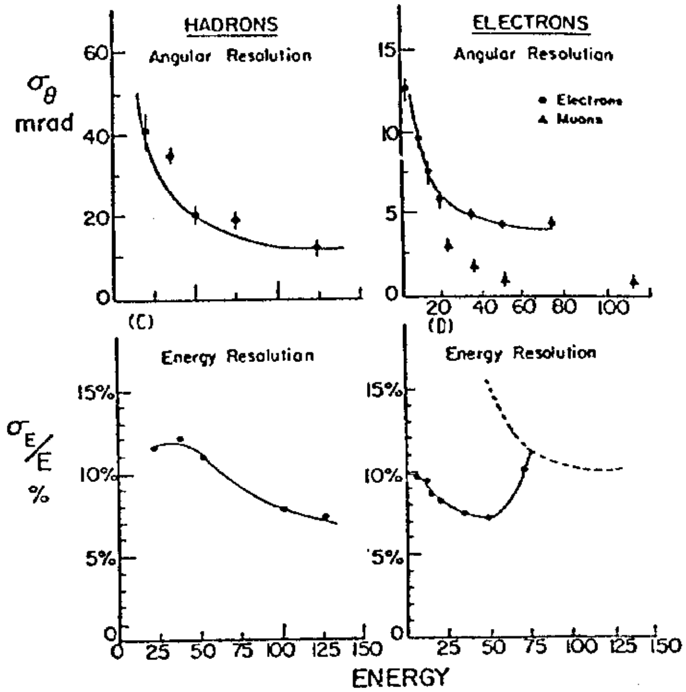

Figure 9. Resolutions of E-594 detector measured in the Fermilab Calibration beam.

cells in a cone of given volume and normalizing ρ to be ~ 1 for electrons (< 1 for hadrons) a cut at $\rho = 0.78$ was found to be about 80% efficient in rejecting hadrons and reduced the number of candidates to 13K. These candidates were each visually scanned by professional Fermilab scanners who, with 95% scan efficiency, reduced the number to $\sim$ 1000 candidates. Physicists then examined each candidate and further reduced the number to 300 events. To improve the signal to background ratio, a fiducial volume cut ($r <$ 110cm) and energy cut (5 GeV $< E_e < 30$ GeV) were introduced. For further analysis, the kinematic variable $E_e\Theta_e^2$ was chosen since this variable is limited to $< 2m_e$ for true $\nu_\mu e$ scatters. The finite energy and angular resolutions of our detector indicated that we would contain 95% of the $\nu_\mu e$ events within $0 < E_e\Theta_e^2 < 6$ MeV so that Figure 10 presents the remaining candidates in 6 MeV bins.

There is an obvious peak in the first bin and we need now separate the signal from the background which has survived all previous cuts. The backgrounds which, in principle, will contribute are:

1. $\nu_e + N \rightarrow e + X$; where E_X is small

2. $\nu_\mu + N \rightarrow \nu_\mu + X$; where the X state is dense

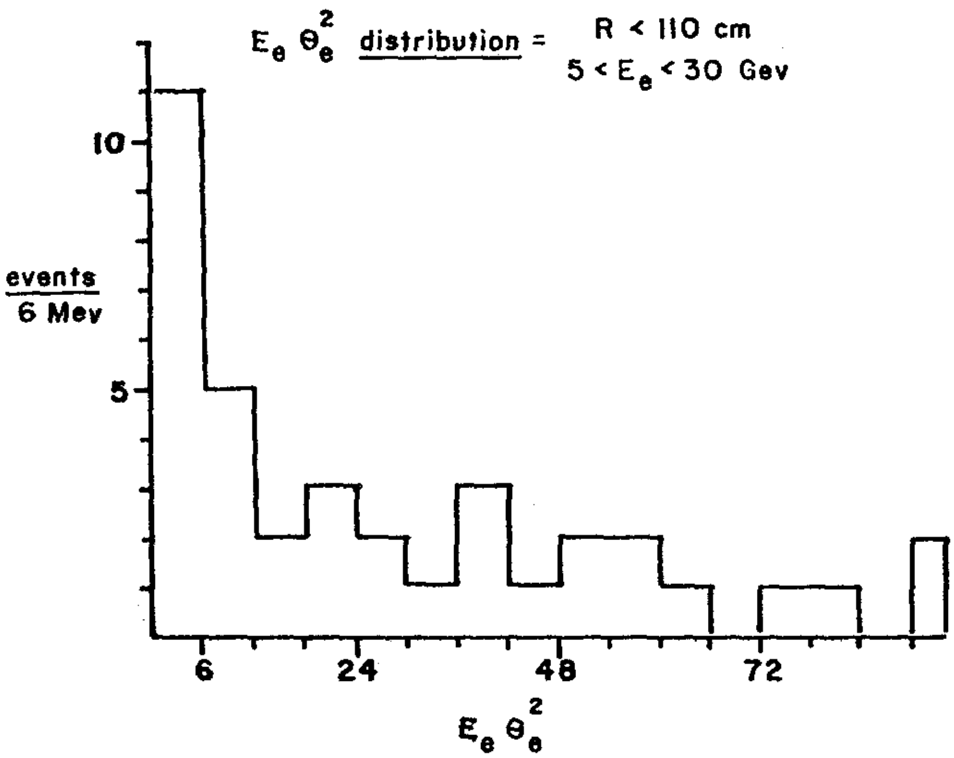

Figure 10. The $E\Theta^2$ distribution of electron candidates surviving the various cuts.

3. $\nu_\mu + N \rightarrow \nu_\mu + N + \pi^0$; Coherent π^0 production

Recent theoretical[13] and experimental [14] results indicate that the third background - ν induced coherent π^0 production - is much larger and more forward peaked than previously assumed. This would imply that all experiments which are unable to consistently distinguish e^+e^- pairs from single electrons should carefully (re)evaluate this background for the given experimental conditions. Within the kinematical cuts of this experiment the expected relative shapes of the three types of backgrounds are shown in Figure 11. The absolute contribution of each source was determined using the relative absolute cross sections of coherent π^0 production[13] and standard CC + NC cross sections, the relative ν_e and ν_μ energy spectra, and shape of the observed $E\Theta^2$ distribution at large $E\Theta^2$ where source 2. is dominant. We find that of the 11 events in the first 6 MeV $E\Theta^2$ bin, 2.4 events are due to source 2; 1.0 event is due to source 1 and 0.9 event is due to neutrino induced coherent π^0 production. This leaves a signal of 6.7 ± 3.6 events which we attribute to $\nu_\mu e$ scattering.

Thus, although the 1981 engineering run did not yield sufficient statistics to add, significantly, to the world sample

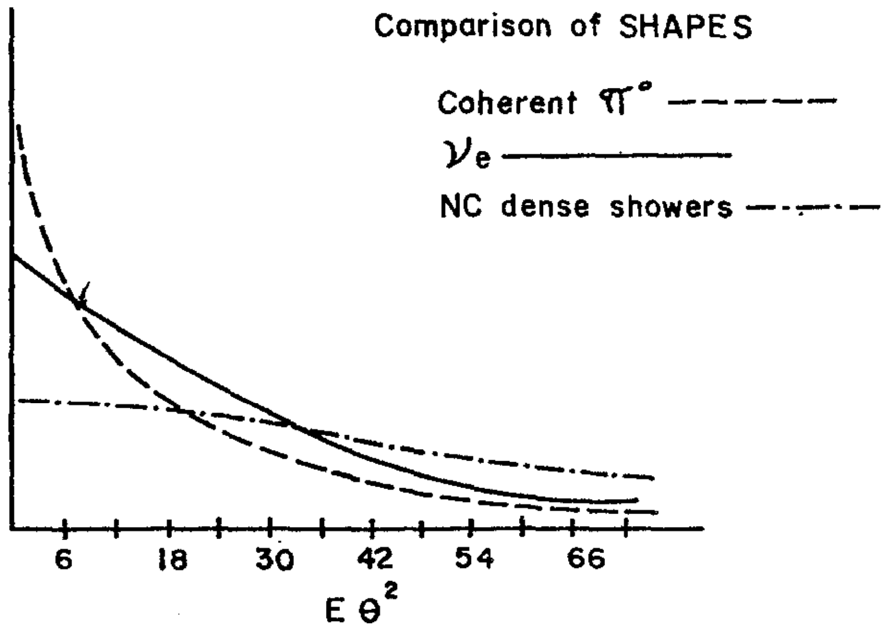

Figure 11. The relative shapes of the three background sources. The curves are all normalized to the same number of events.

of $\nu_\mu e$ events, it did enable us to demonstrate the capability of this fine-grained calorimeter. It furthermore allowed us to emphasize the importance of correctly accounting for the background coming from neutrino induced coherent π^0 production. Had we neglected to account for the very forward peaked distribution of the coherently produced π^0's, we would have underestimated the background by ∿20%.

References

1. F.J. Hasert et.al, Phys. Lett. 46B, 121(1973)
2. L.W. Mo, Review on Purely Leptonic Interactions of Weak Neutral Currents, Proceedings of the Neutrino 1980 Conference, Erice, 1980 and references therein.
3. P.Q. Hung and J.J. Sakurai, UCLA Report UCLA 79/TEP/9; Proc. of Neutrino 79, Vol. 1, 267 (1979).
4. J. Bernabeu and C. Jarlskog, Phys. Lett. 69B, 71 (1977)
5. S. Weinberg, Phys, Rev. Lett, 1264(1967); A. Salam in Elementary Particle Theory, ed. by N.J. Svartholm, 367(1968)
6. J.G. Morfin, Purely Leptonic Neutral Currents, submitted to Deutsche Physikalichses Gesellschaft, 21 February 1983, available as PITHA-69(1973), III Phys. Inst. RWTH Aachen, Germany.
7. J. Blietschau et al., Nucl. Phys. B114, 189 (1976) J. Blietschau et al. Phys. Lett. 73B, 232(1978)

8. L.M. Sehgal, Status of Neutral Currents in Neutrino Interactions, in Proceedings of Neutrino 78, Purdue University 253 (1978).
9. N.J. Baker, Preliminary Results On $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$, in Proceeding of Neutrino 82, Balotonfüred, Hungary, Vol. 2, 1 (1982)
10. B. Borgia, Results on Weak Neutral Currents from the CHARM Collaboration, Proceedings of this conference.
11. Y. Suzuki, Neutrino Electron Results from BNL, Proceedings of this Conference.
12. T.A. Numamaker et al., An Electromagnetic Shower Detector using Proprotional Wire Chambers with Cathode Plane Delay-Line Readout; Virginia Poly. Inst. Preprint VPI-HEP-80/3, February 1980.
13. D. Rein and L. Sehgal, to be published in Nuclear Physics available as III Phys. Inst, RWTH Awachen preprint.
14. E. Isiksal D. Rein and J.G. Morfin, T.H. Aachen preprint PITHA 82/83 submitted to Phys. Rev. Lett.; H. Faissner et al., to be published in Phys. Lett.

FOOTNOTE

F1. At the time of the 1981 engineering run approximately 2/3 of the calorimeter was instrumented and the two 24' proportional planes were not yet in operation.